Gas Dynamic Structure of the Heliosphere: Theoretical Predictions and Experimental Data

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Abstract. Gas dynamic structure of the heliosphere is determined by the solar wind interaction with the supersonic flow of the partially ionized local interstellar medium (LISM). Historical review of this problem investigation is given here. General picture of the considered flow, a mathematical formulation of the gas-kinetic model and its basic results are presented. It is shown that for forecasting of future experimental results it is necessary to construct the models with physically and mathematically correct theoretical basis. Examples of experimental data which can be explained on the basis of theoretical predictions are given. Results of the Ohm’s law analysis for partially ionized hydrogen gas show that a conception of the magnetic field freezing in plasma for the problem of the solar wind interaction with the magnetized LISM flow can be not correct if to take into account the processes of the resonance charge exchange.

INTRODUCTION

Constructing a quantitative theoretical model for the prediction and explanation of experimental data is an important goal in various branches of scientific knowledge. However, such a model is useful if it has a reliable, physically correct theoretical basis (see, for example, [2]); otherwise, an interpretation of the experiments could be wrong. This paper is devoted to a critical survey of the present-day situation in theoretical models of the solar wind interaction with the local interstellar medium (LISM) as well as their role in interpreting a number of observed physical phenomena. A historical review of constructed models in the problem considered is given in Section 2. In Section 3 a qualitative picture of the solar wind interaction with the supersonic LISM flow is considered. A mathematical formulation of the gas-kinetic model by Baranov and Malama [4] is presented in Section 4 and its numerical results are given in Section 5. A number of this model predictions (for example, "hydrogen wall") is analyzed here. Analysis of magnetohydrodynamic (MHD) models is given in Section 6 with point of view of the last results obtained recently in [7].

CRITICAL HISTORICAL REVIEW

Parker [36] was the first who predicted theoretically the solar wind on the basis of the spherically symmetric and one-fluid hydrodynamic equations. In particular, under not very restrictive assumptions concerning a dependence of the temperature on the heliocentric distance $r$ he obtained integral curves for the radial velocity $V$ painted at Figure 1. Here $R_\odot$, $a$ and $r_c$ are solar radius, sound velocity and a point, where $V = a$, respectively. Curve 1 determines the supersonic solar wind. Later this phenomenon was confirmed experimentally by means of spacecraft [17, 35]. However, with theoretical viewpoint the solution for the solar wind should be consistent with the solution for the interstellar medium. Such a self-consistent solution for the interaction of the stellar wind with the interstellar gas was constructed by Parker [37] at assumption that an interstellar gas flow and a stellar wind downwind of the termination shock are incompressible and potential fluid.

The axisymmetric hydrodynamic model of the solar wind interaction with the supersonic flow of the LISM (two-shock model) was first suggested by Baranov et al. in [8] in the thin layer approximation where the thickness of the region between the bow and terminal shocks (heliosheath) is assumed to be small as compared with the distance of this region to the Sun in the upwind direction (Figure 2). To use hydrodynamic equations these authors assumed that the LISM gas is the fully ionized hydrogen gas. Supersonic character of the LISM flow relative to the Sun was experimentally confirmed by Bertaux and Blamont [12] and Thomas and Krassa [42] on the basis of measurements of the scattered solar radiation in Lyman-$\alpha$ on the board of OGO-5 spacecraft, i.e. a motion of the LISM hydrogen atoms with the supersonic bulk velocity ($V_{LISM} \approx 20\text{km/s}$) at the LISM temperature $T_{LISM} \approx 10^4\text{K}$ was discovered by these authors. Therefore, the assumption by Baranov et al [8] that the LISM gas is the fully ionized hydrogen was not correct for the
FIGURE 1. Integral curves of spherically symmetric flow from source. Curve 1 is the solar wind.

problem considered although their two-shock model was used for other branches of astrophysics (see, for example, [15]).

The model by Baranov et al. [8] was reanimated for the problem of the solar wind interaction with the LISM by Wallis [43] who assumed, that the LISM is a partially ionized gas, and showed that plasma component (electrons and protons) and H-atoms can influence each other by resonance charge exchange effects. This mutual influence has two aspects. First, the plasma heliosheath becomes a kind of a "filter" for LISM hydrogen atoms, i.e. their parameters are changed after penetrating the solar system. Second, the resonance charge exchange processes can affect plasma parameters, change the heliosheath structure, its size, and its distance from the Sun. These effects were not taken into account till 1985 at the interpretation of measurements of the solar Lyman $\alpha$ scattered radiation (see, for example, [13]).

At present there is no doubt that the LISM is partially ionized gas where the main component is partially ionized hydrogen. A revolution in this region was made due to ground observations by Lallement and Bertin [28] and an interpretation of observations by GHRS instrument on Hubble Space Telescope (HST) [29]. They showed that the solar system is embedded in the local interstellar cloud (LIC) moving relative to the Sun with the velocity $V_{LIC}=25.7 \pm 0.5 \text{km/s}$ and temperature $T_{LIC}=7000 \text{ K}$. This is a supersonic flow with the Mach number $M_{LIC}=V_{LIC}/a_{LIC} \sim 2$, where $a_{LIC} = \sqrt{\gamma RT_{LIC}/\rho}$ and $R$ are the specific heat ratio and gas constant, respectively. These parameters of LIC were recently confirmed by the Neutral Gas Experiment [44] on board of the Ulysses spacecraft. Their results were obtained on the basis of helium atom measurements. Helium atoms do not interact with heliosheath due to their small charge exchange cross section with protons.

In 1981 Baranov et al. [9] constructed an simplified axisymmetric model of the solar wind interaction with the supersonic LISM flow self-consistently taking into account mutual influence of plasma component and the LISM H-atoms due to processes of the resonance charge exchange. To estimate effects of H-atoms on the plasma structure of the heliosphere they used the hydrodynamic equations for the plasma component with "source terms" [20], the simplified continuity equation for H-atom only with disappearing H-atoms due to resonance charge exchange (secondary H-atoms did not take into account) and a crude assumption that temperature $T_H$ and bulk velocity $V_H$ of H-atoms are constant. The last assumption was made due to mean free path of H-atoms is comparable with characteristic size of the problem (for example, with the size of the heliosphere) and hydrodynamic momentum and energy equations are not correct in this case. We would like to note here that this simplified model for H-atoms was used in [30] for calculation of 3D MHD problem. However, this model gives rise to good results for plasma component in the vicinity of the upwind direction, but it is absolutely unfit for the tail region and for the interpretation of scattered solar Lyman $\alpha$ experiments.
FIGURE 2. Qualitative picture of the first model of the solar wind interaction with supersonic flow of the LISM. Thin layer approximation

QUALITATIVE PICTURE OF THE FLOW CONSIDERED

General picture of the flow caused by the interaction of the solar wind with the supersonic partially ionized hydrogen LISM in Figure 3 is shown. Here the heliopause (HP) is tangential (or contact) discontinuity separating the LISM plasma component and the solar wind. The bow shock (BS) is formed in the supersonic LISM plasma component due to its deceleration at approach to an "obstacle" (here to the HP). The termination shock (TS) is also formed due to deceleration of the solar wind. The heliosheath is the region between the BS and the TS. This region is separated on the outer heliosheath (between BS and HP) and the inner heliosheath (between TS and HP). Of course, geometrical pattern with strong discontinuities (shocks and tangential discontinuity), presented in Figure 3, can be formed only in a hydrodynamic approximation. It can be justified for plasma component rather than for H-atoms, because $Kn = l/L \cdot 1$ for the H-atoms in the problem of the solar wind interaction with the LISM, where $Kn$, $l$ and $L$ are Knudsen number, mean free path of H-atoms for resonance charge exchange processes and characteristic size of the problem (for example, the size of the heliopause), respectively. In this case a description of H-atom motion in the framework of a hydrodynamic approximation is not correct.

Hydrogen atoms from the LISM penetrating through the four regions presented in Figure 3 are subjected to charge exchange with protons of the plasma component. Since the protons in regions 1 - 4 have different parameters (for example, the temperature and the bulk velocity), the four populations of H-atoms are distinguished by different parameters due to their different places of birth. Population 1 is born in region 1 by the charge exchange of hydrogen atoms from the LISM with supersonic solar wind protons. This population has a large bulk velocity of antisolar direction compared with the thermal velocity. Population 2 is formed as a result of charge exchanges between the hydrogen atoms from the LISM and the solar wind protons thermalized downstream of the TS (in the inner heliosheath). Population 2 of H-atoms has relatively small local bulk velocity and large thermal velocity. Population 3 consists of secondary interstellar H-atoms which are born in region 3 (outer heliosheath) by the charge exchange of interstellar protons thermalized downstream of the BS with the hydrogen atoms from the LISM. Baranov et al. [10] have shown that the number density of this population has no monotonic distribution with heliocentric distance. The maximum of this distribution (the "hydrogen wall") is localized in the vicinity of the HP. Population 3 can also be formed in the disturbed part of the region 4. This disturbed part is formed upwind of the BS due to charge exchange of Populations 1 and 2 of H-atoms and the LISM protons [18]. Population 4 represents primary H-atoms that move from the
undisturbed LISM into the solar system without undergoing charge exchanges. Populations 3 and 4 are measured in the solar scattered Lyman $\alpha$ experiments.

We considered in this Section the qualitative picture of the flow considered. However, it is necessary to construct a mathematical model to obtain quantitative results. As we seen from Introduction, such a model must have a reliable, physically correct theoretical basis to interpret experimental data correctly. Next Section will be devoted to the model by Baranov and Malama (1993) [4], where the plasma component is described by hydrodynamic equations which must take into account the momentum and energy changes due to processes of resonance charge exchange, i.e. these equations must have "source" terms taking into account this effect of H-atoms on the plasma component. For a stationary problem the equations of mass, momentum and energy conservation for ideal gas have the following form (one-fluid approximation for plasma component)

$$\nabla \cdot \rho \vec{V} = 0,$$

$$\nabla \cdot \left( \frac{1}{\rho} \nabla p \right) = F_1[f_H(\vec{r}, \vec{w}_H), \rho, \vec{V}, p],$$

$$\nabla \cdot \left[ \rho \vec{V} (e + p/\rho + \vec{V}^2/2) \right] = F_2[f_H(\vec{r}, \vec{w}_H), \rho, \vec{V}, p],$$

$$p = (\gamma - 1) \rho e,$$

where $\rho$, $\rho$, $\vec{V}$ and $e$ are pressure, mass density, bulk velocity and internal energy, respectively; $\gamma$ is the ratio of specific heats; $F_1$ and $F_2$ are the functionals, describing the change of momentum and energy of the plasma component due to collisions between H atoms and protons which characterize the resonance charge exchange ("source" terms); and $f_H(\vec{r}, \vec{w}_H)$ is the H atom distribution function depending on position-vector $\vec{r}$ and the indi-
individual velocity $\vec{v}_H$ of H-atoms. The distribution function must satisfy the Boltzmann equation

$$\vec{v}_H \cdot \frac{\partial f_H(\vec{r}, \vec{v}_H)}{\partial \vec{v}_H} + [ (\vec{F}_1 + \vec{F}_2) / m_H ] \cdot \frac{\partial f_H(\vec{r}, \vec{v}_H)}{\partial \vec{r}} = 0$$

Equation (2) $f_p$ is the local Maxwellian distribution function of protons with gasdynamic values $p(\vec{r})$, $\vec{V}(\vec{r})$ and $T(\vec{r})$ which satisfy to hydrodynamic equations (1), $\vec{w}_p$ is the individual velocity of a proton, $\vec{F}_1$ and $\vec{F}_2$ are the force of the solar radiation pressure and the solar gravitational force, respectively, and $\sigma$ is the cross section of the resonance charge exchange. If the distribution function $f_p$ is known the "source" terms $\vec{F}_1$ and $\vec{F}_2$ in equations (1) can be calculated exactly. We have in this case

$$\vec{F}_1 = \frac{1}{n_p} \int d\vec{w}_p \sigma \left( \vec{w}_H - \vec{w}_p \right) f_H(\vec{r}, \vec{w}_H) f_p(\vec{r}, \vec{w}_p)$$

$$\vec{F}_2 = m_H \int d\vec{w}_H \left( \int d\vec{w}_p \sigma \left( \vec{w}_H - \vec{w}_p \right) f_H(\vec{r}, \vec{w}_H) f_p(\vec{r}, \vec{w}_p) \right)$$

$$n_H = \int d\vec{w}_H f_H(\vec{r}, \vec{w}_H)$$

However, Baranov and Malama in [4] used Monte Carlo method to solve numerically the Boltzmann equation (2). The trajectories of H atoms were calculated by the complicated Monte Carlo scheme with "splitting" of trajectories [32] in the field of the plasma gasdynamic parameters. Such an approach allows to calculate the "source" terms in the equations (1) in the framework of a kinetic description of H-atoms if to use formulae (3) (multiple charge exchange are also taken into account by this Monte Carlo method). The solar wind was assumed to be spherically symmetric. That is why the problem was considered as axisymmetric.

To solve the system of equations (1) - (3) the following physical boundary conditions for plasma component were used: the Rankine-Hugoniot relations on the shock waves BS and TS (see Figure 3); the equality of pressures and vanishing normal component of the plasma bulk velocity on the heliopause HP (tangential or contact discontinuity); the velocities, proton (electron) number densities and Mach numbers were given in the undisturbed LISM (index "∞") and at the Earth orbit (index "E").

To calculate H-atom trajectories and "source" terms the distribution function $f_H$ was assumed to be Maxwellian in the undisturbed LISM (at infinity) with the temperature $T_\infty$, number density $n_{H\infty}$, and velocity $V_\infty$. In so doing, the motion of H atoms is also determined by the solar gravitation force, the force of solar radiation pressure and resonance charge exchange. Any later [6] effects of the photoionization of H atoms near the Sun and H atom ionization due to electron impact in the inner heliosheath were also taken into account. Nonreflecting conditions on the right boundary of the computation region were used. A global iterative method for solution of the problem, suggested in [10] and completed in [4] consists of several steps. First, the trajectories of H atoms were calculated by Monte Carlo method in the field of plasma parameters obtained without "source" terms for fully ionized hydrogen (see, for example, the zero iteration made in [10]). Than the momentum and energy "sources" $\vec{F}_1$ and $\vec{F}_2$ (1) were calculated in this step of iteration using equations (3). In the first iteration, the hydrodynamic equations (1) with these "sources" were solved using the gasdynamic boundary conditions formulated above. Then, the new distribution of plasma parameters was used for the next Monte Carlo iteration for H atoms. The gasdynamic problem was solved again with the new "source" terms of this iteration (the second iteration) and so on. This process of iterations was continued until the results of two subsequent iterations practically coincide. To solve the gasdynamic part of the problem numerically Baranov and Malama (1993) have used the discontinuity-fitting "second order" technique, which is based on the scheme of Godunov’s method [16].

BASIC RESULTS OF GAS-KINETIC MODEL

Formulated in Section 4 model is numerically solved at different parameters given in the undisturbed LISM and at the Earth orbit. Below we will present the basic results separately for plasma component and for H-atoms of several populations for the following values of the specific parameters

$$n_{pE} = 7 cm^{-3}, V_E = 450 km/s, M_E = 10, \ V_\infty = 25 km/s, M_\infty = 2, \ n_{p\infty} = 0.07 cm^{-3}, n_{H\infty} = 0.14 cm^{-3}, \ \mu = F_i / F_E = 0.75$$

We will also compare the results of our theoretical predictions with the experimental data obtained with spacecraft. In so doing, direct and indirect (remote) methods can be used to detect physical phenomena in space. For example, at present the parameters of inner and outer heliosheaths (regions 2 and 3, respectively, in Figure 3) can be detected only by indirect methods although in fu-
ture they can be detected by direct methods after crossing Voyager spacecraft the TS or after realization in USA of the Interstellar Probe project. However, direct measurements of the solar wind parameters and the LISM helium atom parameters in region 1 by Voyager and Ulysses spacecraft are now continuing.

Basic results for plasma component

One of the main results of the axisymmetric model, described in Section 4, is the geometrical pattern of the heliosheath. Figure 4 shows the BS, TS, and HP shapes and their heliocentric distances in the xOz plane at the boundary magnitudes of parameters (4). Here the Oz axis coincides with axis of symmetry and is antiparallel to the vector of the LISM’s velocity $V_{\odot}$ (the Sun is in the center of the coordinate system). The Ox axis is normal to the Oz axis.

We see from Figure 4 that heliocentric distances to the TS, HP and BS in the upwind direction are equal about 100 A.U., 180 A.U. and 550 A.U., respectively. The distance to the TS in the downwind direction is more and equal about 160 A.U., i.e. the termination shock is not a sphere. For comparison, Figure 4 demonstrates the geometrical pattern at $n_{H_{\odot}} = 0$. We see that effect of the resonance charge exchange gives rise, first, to decreasing the heliocentric distances of the BS, HP and TS, second, to a smooth shape of the TS (without triple point A and Mach disc MD) and, third, to a subsonic flow in the inner heliosheath.

The following effects in the distant supersonic solar wind due to processes of resonance charge exchange were predicted in [4]: (i) the decrease of the solar wind velocity; (ii) the deviation of the proton number density from the law $1/r^2$; and (iii) the increase of the plasma temperature with the distance from the Sun. However, the last effect is theoretically too large due to using the one-fluid model, where temperatures of electrons and protons are equal. It is interesting to note here that there are direct experimental detections of such effects obtained by Voyager 1/2 observations (see [14]). For example, the deceleration of the solar wind velocity as 30 km/s (about 8% of the average velocity 450 km/s) was estimated from these experiments. It is coinciding with the predictions by Baranov and Malama [4] in the upwind direction. At present indirect observations confirmed theoretical predictions that the outer heliosheath (the region 3) is formed in the problem considered. This conclusion follows, for example, from a detection of the "filter" effect, mentioned above, for the LISM H atoms and its absence for LISM He atoms (see, for example, [44, 27]) due to small cross section of charge exchange between He-atoms and protons.

Basic results for hydrogen atoms

Parameters of four populations of H atoms mentioned in Section 3 were separately calculated on the basis of the model by Baranov and Malama [4]. A basic result is connected with Population 3, i.e. with the secondary LISM H - atoms. The number density of this Population has non-monotonic character with maximum in the vicinity of the HP [10, 4]. This effect was named as "hydrogen wall". The hydrogen wall was experimentally discovered by Linsky and Wood [31] on the basis of interpretation of the Lyman $\alpha$ absorption profile obtained by the GHRS instrument on the HST spacecraft (in details, see, for example, [3]). Basic scheme of such measurements in Figure 5 is painted. Linsky and Wood [31] could only explain the absorption spectrum for the $\alpha Cen$ line of sight (52$^0$ from upwind direction) by including absorption by the heliospheric hydrogen wall (Figure 5). It should be noted here that the largest changes in the hydrogen wall properties (H-atom heating, bulk velocity deceleration and maximum of the H-atom number density) from their ambient values occur in the upwind direction. That is why the star 36OphA, which is only 12$^0$ from the upwind direction was observed in [45] with STIS instrument on HST. Their results show that the properties of the heliospheric absorption are consistent with previous measurements of this absorption for the $\alpha Cen$ line of sight.

Thus the experimental discovery of the heliospheric hydrogen wall predicted theoretically in [10] is now confirmed by the absorption due to secondary neutral hydrogen atoms formed in the vicinity of the HP. Detailed analysis of the Lyman - alpha absorption profile for different lines of sight shows that hydrogen walls are presented around other stars with sufficiently strong winds [46].

The Lyman-$\alpha$ absorption profile toward Sirius (139$^0$ from upwind direction) obtained by GHRS instrument on the HST (see Figure 5) was analysed by Izmodenov et al. (1999). They showed that the observed properties of the absorption cannot be explained without taking into account energetic H- atoms (Population 2) in the inner heliosheath, because the hydrogen wall is not easily observable almost in the downwind direction toward Sirius. Detailed study of Lyman $\alpha$ absorption toward six nearby stars was done in [25].

We also believe that the inner heliosheath image in the energetic H-atom (Population 2) fluxes with 1 A.U. planned in USA (see, for example [19]) is a very promising method for detecting the inner heliosheath, because such measurements could be carried out regularly. Theoretical calculations of these fluxes and their anisotropy (from upwind to downwind directions) for different assumed ionization fractions in the LISM were obtained in [23].
FIGURE 4. Results of calculations. Left picture is results for \( n_H = 0 \). A is triple point. Right picture is results for \( n_H \neq 0 \).

FIGURE 5. Schematic picture of Lyman-alpha absorption experiment (HST).
It is necessary to note here, that the distribution function of H-atoms which is Maxwellian in the LISM becomes quickly non-Maxwellian at crossing interface region between the solar wind and the LISM. This result was first obtained in [11] on the basis of calculations of H-atom moments and was confirmed in [21, 24] on the basis of calculations of H-atom distribution function. Therefore, the hydrodynamic approximation for H-atoms, used by several authors, are not correct in the problem considered. It is naturally because Knudsen number $Kn = l/L \sim 1$ for H-atoms as mentioned in Section 3.

ON THE PROBLEM OF THE INTERSTELLAR MAGNETIC FIELD FREEZING FOR THE PARTIALLY IONIZED LISM.

Many authors have been studied the problem of the solar wind interaction with the magnetized LISM without taking into account H-atoms [5, 33, 38, 39, 40, 41] and with taking into account resonance charge exchange processes [30, 1]. The equation for a vector of magnetic field induction $\mathbf{B}$ in a form

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

(5)

was used in these papers. This equation determines MHD conception of the magnetic field freezing in plasma. However, as we have seen above, the LISM hydrogen atoms and processes of resonance charge exchange connected with these atoms play a determining role in the problem of the solar wind interaction with the LISM. That is why the first group of papers, where were considered MHD problems without taking into account H-atoms, have only a theoretical interest for MHD rather than for problem considered. Recently, the conception of the magnetic field freezing in partially ionized interstellar gas was considered in [7]. Analyzing the Ohm law for partially ionized hydrogen gas and taking into account processes of the resonance charge exchange these authors showed that the last processes give rise to the equation of the magnetic field induction in a form

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \nabla \times \left[ \frac{(1 - \alpha)^2}{\sigma B^2} \right]$$

(6)

\[
\left( \frac{\alpha}{1 + \alpha} \right) \nabla p \times \mathbf{B} - \frac{1}{4\pi} \mathbf{B} \times (\nabla \times \mathbf{B}) \times \mathbf{B}
\]

where $\alpha$ is a degree of ionization ($\alpha = 1$ is for the fully ionized hydrogen). The equation (6) coincides with the equation (5) only at $\alpha = 1$. Estimations in [7] show that the last term on the right side of the equation (6) can be comparable or more with the first term on the right side of this equation, i.e. the results of second group of papers could be reconsidered although the results by Baranov and Fahr [7] are obtained in hydrodynamic approximation. An investigation of this problem must be continued.

CONCLUSION

In conclusion we would like to discuss effect of other physical phenomena on the axisymmetric model formulated in Section 4.

1. Effect of Galactic Cosmic Rays (GCR) is practically negligible as compared with the effect of resonance charge exchange [34].

2. At present our group has the preliminary results of anomalous cosmic rays (ACR) effect. Effect of ACR gives rise to a change of TS structure and, therefore, to some changes of distribution of plasma and neutral component parameters in the inner heliosheath.

3. Results obtained on the Ulysses spacecraft showed that the solar wind is not spherically symmetric. Therefore, it is necessary to construct 3D self-consistent model of the solar wind interaction with the LISM. At present the problem is in progress in our group.

4. Our group constructed gas-kinetic time dependent model of the solar wind interaction with the LISM taking into account effects of the solar cycle [47, 26].

5. It is necessary to reconstruct models of the solar wind interaction with magnetized partially ionized LISM with kinetic point of view taking into account processes of resonance charge exchange [7].

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